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POSTER SESSION

Influence of the spatial frequency on the diffractive optical elements fabrication in PDLCs

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ABSTRACT

Photopolymers are classical holographic recording materials. Recently their chemical composition and the fabrication techniques have been optimized for many new applications such as interconnectors, solar concentrations, 2-D photonic structures, or wave-guides. Their potential usefulness has been drastically increased by the introduction of dispersed liquid crystal molecules; these components can be concentrated in the non-exposed zones of the material by a photopolymerization induced phase separation process (PIPS). Therefore, by combining polymer and dispersed liquid crystal (PDLC) has emerged as a new composite material for switchable diffractive optical elements (DOEs). Parallel to the material advances some techniques have been proposed to record very low spatial frequencies DOE's. Different researchers have reported proposes to record DOE like fork gratings, photonics structures, lenses, sinusoidal, blazed or fork gratings. In this work we have studied the behavior of a PDLC material to record DOE's with different spatial periods: from 1 µm, using holographic technique, to more than 200 µm, Liquid Cristal on Silicon (LCoS) display working in mostly amplitude mode as a master. Due to the improvement in the spatial light modulation technology and the pixel miniaturization, this technique permits us store gratings with spatial frequencies until few microns. Additionally, this technology permits us an accurate and dynamic control of the phase and the amplitude of the recording beam. In particular, for our case, to generate the blazed gratings, we use an LCoS-Pluto provided by Holoeye with a resolution of 1920x1080 (HDTV) pixels and a pixel size of 7.7x7.7 m^2.

Keywords: holography, holographic recording materials, diffractive optical elements, HPDLC, photopolymers, spatial light modulator

1. INTRODUCTION

Photopolymers are one of the most promising holographic recording media for many technological applications, from integrated optical waveguide fabrication to optical data storage [1–5]. Their versatility is well known and new possibilities were created by including new components, such as nanoparticles or dispersed liquid crystal molecules in classical formulations, making them interesting for additional applications in which the thin film preparation and the structural modification have a fundamental importance [6–8].

The incorporation of liquid crystals in photopolymers makes it possible to obtain composite materials which can vary their optical properties by means of an electric field. The liquid crystal molecules add optical anisotropy to the photopolymer and therefore it is possible to change the response modifying the electric field applied [9–16]. For example, the ability to control the diffraction efficiency of holographic optical elements by applying an electric field leads to the possibility of using HOEs in dynamic applications for agile beam steering, nonlinear optics, and optical switching devices [17].

Holographic polymer dispersed liquid crystals are known as H-PDLCs. They are made by holographic recording in a photopolymerization induced phase separation process (PIPS) in which the liquid crystal molecules diffuse to dark zones in the diffraction grating where they can be oriented by means of an electric field. The orientation of the liquid crystal produces a refractive index variation which changes the diffraction efficiency. Therefore, the grating develops a dynamic

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behavior that may be modified by electronic means. In this manner, it is possible to make dynamic devices such as tunable-focus lenses, sensors, phase modulators, or prism gratings [18–24].

Our study is centered on the recording of low spatial frequency diffractive optical elements (DOEs). The viability of different photopolymeric materials to record DOEs like lenses, axicons or blazed gratings has been analyzed widely in previous studies [25-29] and in this case, we have studied the behavior of an HPDLC material to record DOE's with different spatial periods: from 1 μm, using holographic technique, to more than 200 μm, using a Liquid Cristal on Silicon (LCoS) display working in mostly amplitude mode as a master.

2. EXPERIMENTAL SECTION

The monomer used was dipentaerythritol penta/hexa-acrylate (DPHPA) with a refractive index n = 1.490. We used the nematic liquid crystal CL036 (LC) from Qingdao Intermodal Co., Ltd., which is a mixture of 4-cyanobiphenyls with alkyl chains of different lengths. It has an ordinary refractive index n0 = 1.520 and a difference between extraordinary and ordinary index $\Delta n = 0.250$. N-Vinyl-2-pyrrolidone (NVP) was used as crosslinker and octanoic acid (OA) as cosolvent and surfactant.We used ethyl eosin (YEt) as dye and N-phenyl glycine (NPG) as radical generator. N-Methyl-2-pyrrolidone was used in combination with NVP, a solution obtained in a previous study, in order to control the overmodulation during hologram recording [30]. Table 1 shows the composition of the material.

The composite solution was made by mixing the components under red light where the material is not sensitive. The solution was sonicated at 35°C in an ultrasonic bath, deposited between two ITO conductive glass plates 1mm thick, and separated using 30 μm glass microspheres from Whitehouse Scientific Ltd.

Once exposed, a photopolymerization reaction takes place in the bright zones of the diffraction grating and a highly reticulated polymer network is generated. During the PIPS, the liquid crystal molecules diffuse to the unexposed region where they remain as droplets.

Table 1. Composition for LC-photopolymer composite in wt%.

DPHPA	CL036	Yet	NPG	NVP	OA	NMP
46.52	29.31	0.08	0.94	15.80	4.22	3.13

To record and evaluate the recording of sharp DOEs, the setup shown in Figure 1 was used. A solid-state Verdi laser (Nd-YVO4) with a wavelength of 532 nm (green light), at which the material exhibits maximum absorption, was used during the recording process.

In the setup, we can distinguish two beams, the recording beam and the analyzing beam. The periodic pattern, in this case the blazed grating, is introduced by a Liquid Crystal on Silicon (LCoS) modulator placed along the recording arm of our setup and sandwiched between two polarizers (P) oriented to produce amplitude-mostly modulation. Then, with a 4f system the intensity distribution generated by the LCoS is imaged onto the recording material. In this work, we have used a recording intensity of 0.1 mW/cm2, because the different photopolymers tested present an acceptable response and we can analyze the diffraction efficiencies in real time.

The analyzing arm is made up of a He-Ne laser at a wavelength of 633 nm, at which the material exhibits no absorption, used to analyze in real time the elements formed on the material. This arm is designed to collimate the light incident on the recording material and a diaphragm (D1) was used to limit the aperture of this collimated beam of light. A non-polarizing beam splitter (BS) was used to make the two beams follow the same path up to the red filter (RF) placed behind the recording material to ensure that only the analyzing beam is incident on the CCD placed at the end of the setup. To separate the different diffraction orders, we placed a lens behind the material, obtaining the Fraunhofer diffraction pattern on the camera. We used a high dynamic range CCD camera model pco.1600 from pco.imaging. This camera has a resolution of 1600 x 1200 and a pixel size of 7.4 μm x 7.4 μm The camera was also used in the plane of the recording material to evaluate the intensity pattern actually imaged from the LCD plane.

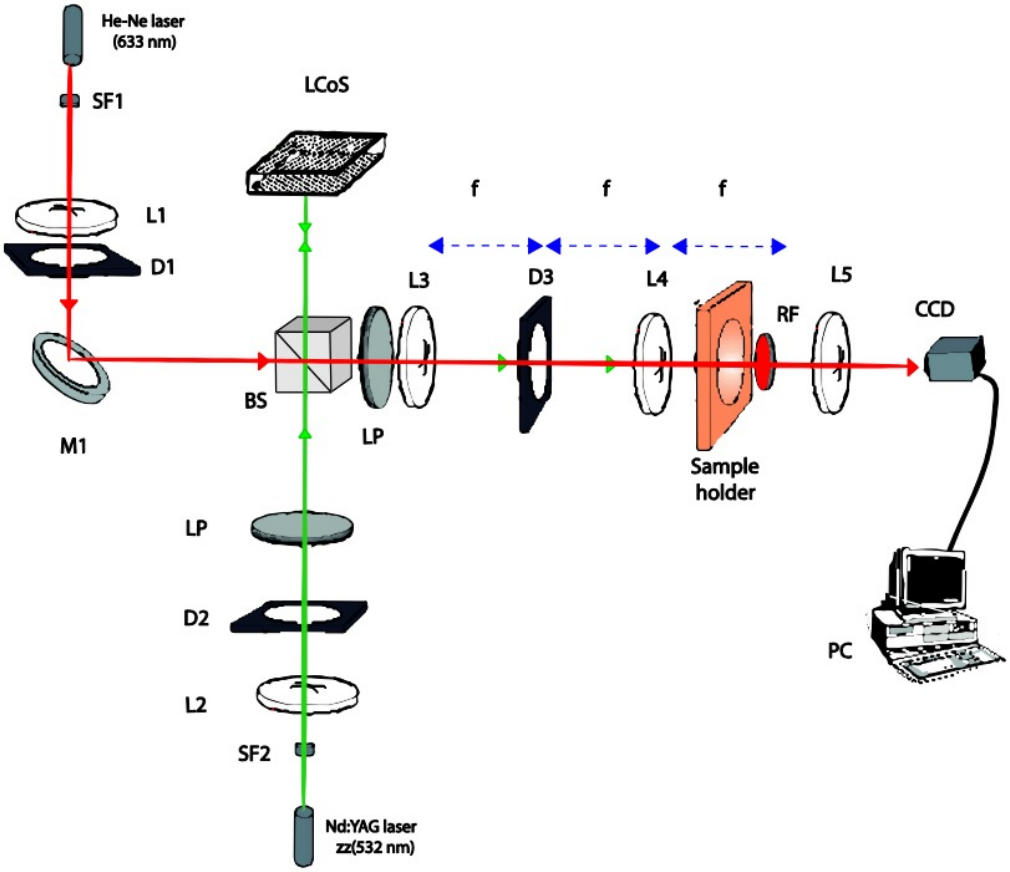


Figure 1. Experimental setup. BS: beam splitter, Mi: mirror, SFi: spatial filter, Li: lens, Di: diaphragm, Oi: optical power meter, and PC: data recorder.

An example of the images obtained by the CCD camera located in the recording plane are shown in Figure 2a and some examples of intensity distributions are shown in Figure 2b and 3. The Figures 2b and 3 show the effects of low pass filtering on the final DOE due to the diaphragm used to eliminate the diffraction orders produced by pixilation of the LCD, as mentioned previously. These figures show a smoothed form of the abrupt edges that take place on the recording intensity distribution with a grating period of 1448 μm and 40 μm. In the fig 3, due to the smaller size of the grating, the low pass filtering is more accused causing the total loss of the blazed profile having a sinusoidal form.

This intensity pattern is the one that will be recorded on the photopolymeric material converted into a phase element, improved by the inclusion of the LCoS with a pixel size of 8 μm as opposed to the transmition of LCD with a pixel size of 44 μm used in previous studies. This new spatial light modulation opens up a great number of possibilities such as recording symmetric and asymmetric holographic patterns using a single beam [31] or cylindrical or spherical diffractive lenses [32] as well as greatly improving the resolution of diffractive optical elements [33], as in the case of our study.

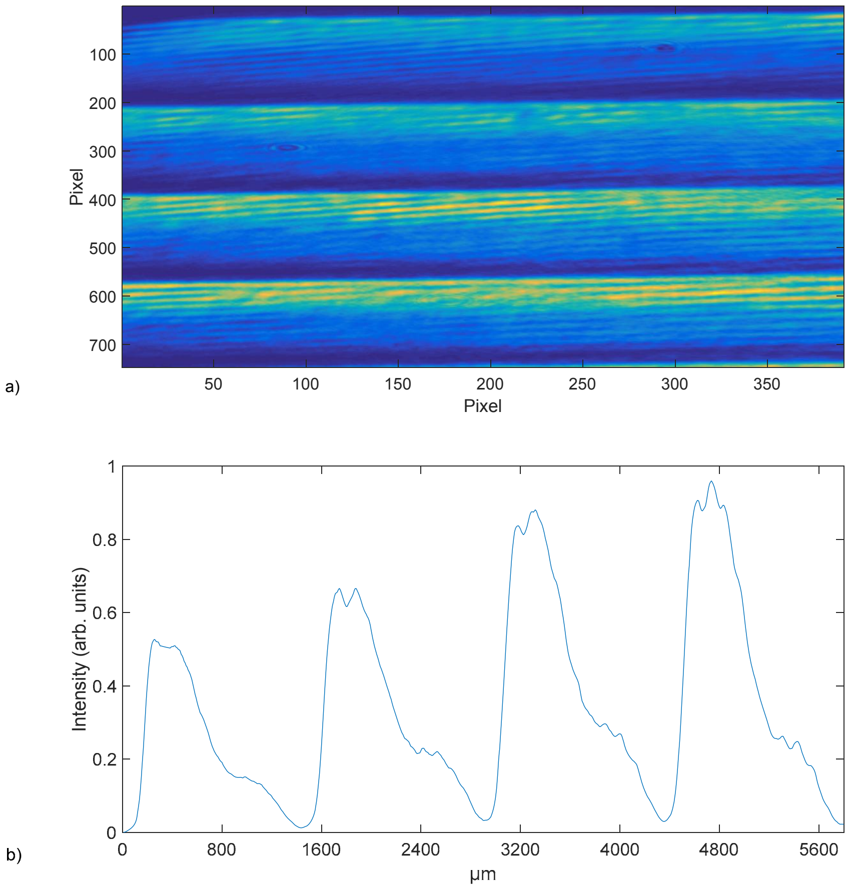


Figure 2. (a) The image on the photopolymer provided by the LCoS and captured by the CCD camera; and (b) the intensity profile provided by the LCoS across a vertical line of the image in (a) for a 1448 μm period blazed grating.

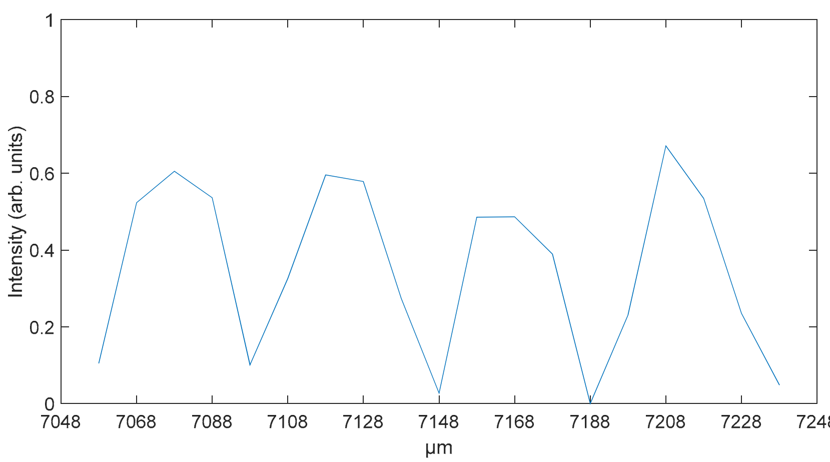


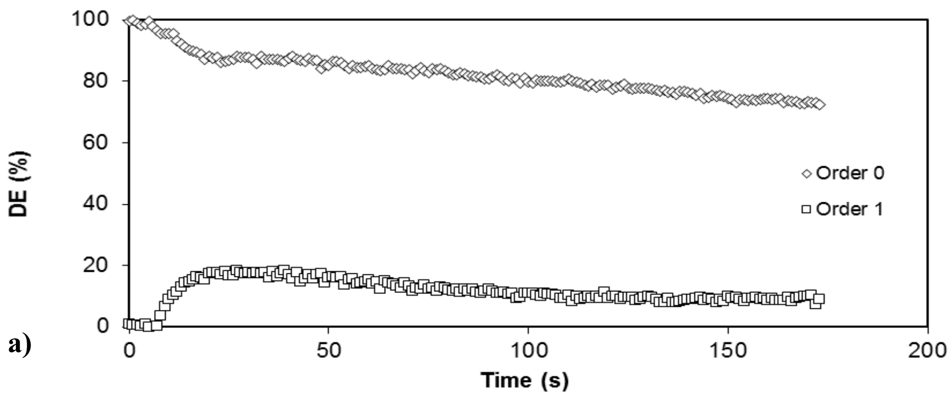
Figure 3. Intensity profile provided by the LCoS across a vertical line for a 40 μm period blazed grating.

The devices are exposed to an electrical field in order to evaluate the electro-optical response. The electro-optical set-up includes a Tektronik TDS1012B oscilloscope, Tektronic AFG3022B dual channel arbitrary function generator, N4L voltage amplifier, and an impedance control circuit designed in our laboratory. The signal applied to the device is adjusted to AC, 1 kHz bipolar square waveform. The impedance control circuit attenuates the high intensity spikes associated with capacitance effects produced by the steep voltage changes in the applied voltage.

These intensity spikes reach values higher than the ones allowed by the amplifier protection circuit, thus switching it off and limiting the range of the applicable high voltage amplitude values. The capacitance is due to the capacitor structure of the H-PDLC cell, composed of the two ITO electrodes and the H-PDLC dielectric layer in between.

3. RESULTS AND DISCUSSION

After recording the DOE, our first aim was to analyze the influence of the period of the grating on the DOE recording, then, the device is placed into an electrical field in order to evaluate the electro-optical response. Figure 4 shows the diffraction orders of a 1448 µm, 160 µm and 80 µm blazed gratins recorded with a recording intensity of 0.1 mW/cm2. It may be seen that in the three figures the diffraction efficiency (DE) of the first order increases and reaches a maximum value above the 20% after an exposure time of 30 s for the 1148 and 160 µm gratings and showed a slower behavior for the 80 µm but reaching almost the 40% of DE.



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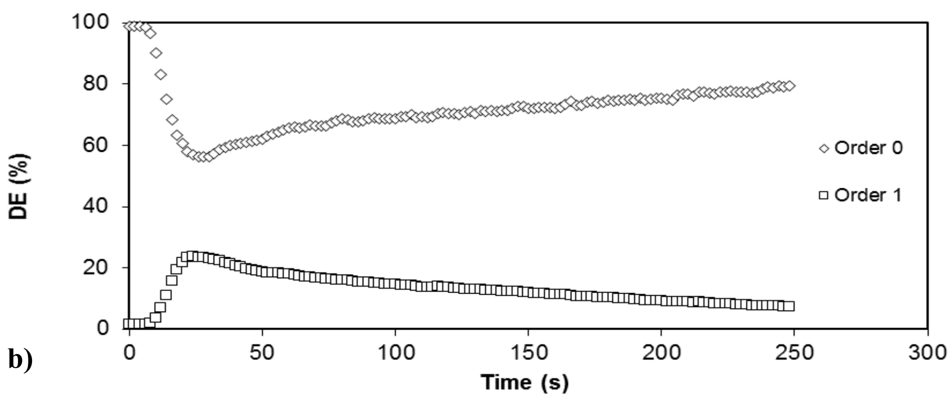

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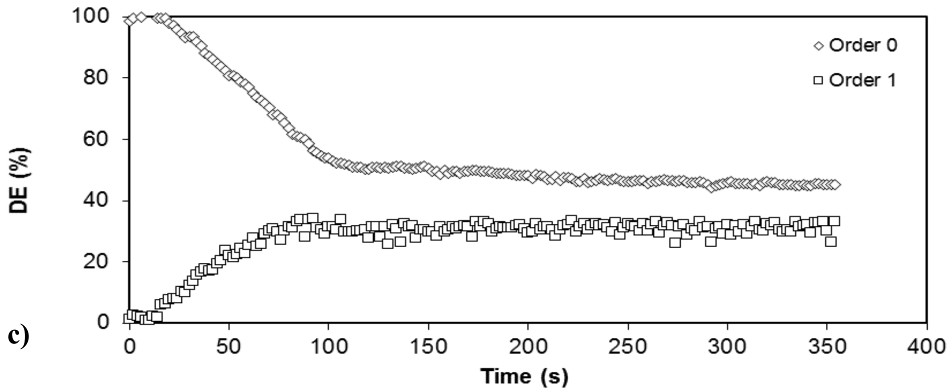
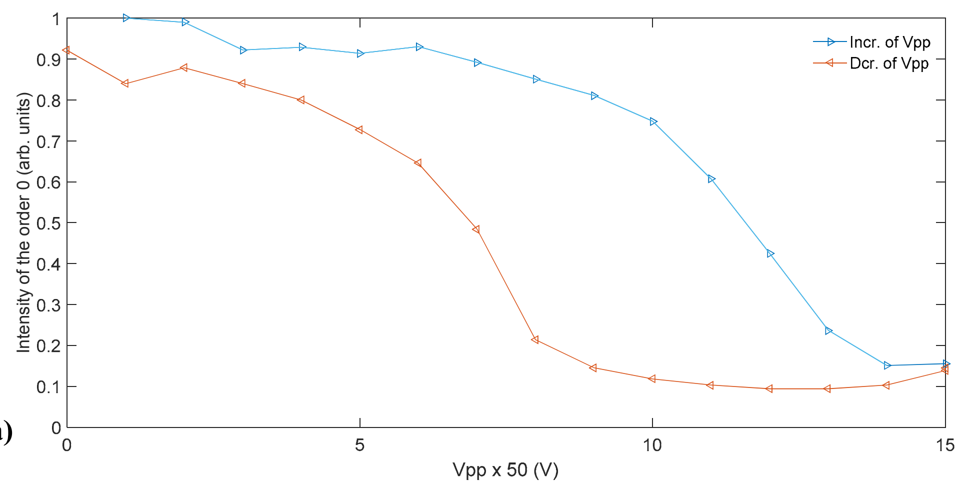


c)

Figure 4. (a) Diffraction efficiency of the main and first order as a function of time for a 1448 μm period blazed grating, (b) diffraction efficiency of the main and first order as a function of time for a 160 μm period blazed grating, (c) diffraction efficiency of the main and first order as a function of time for an 80 μm blazed grating.

After recording of the hologram, the device is placed into an electrical field in order to evaluate the electro-optical response. Figure 5 shows the changes onto the intensity of the zero order for the 1448 μm period blazed grating and first orders for the 160 μm and 80 μm period blazed gratings as function of the of the applied voltage. In figure 5 (a) is shown how a reduction in the intensity is produced with the increasing of the Vpp, reaching a decrease of the 80% of the intensity for 750 Vpp, the maximum value of Vpp allowed by the ITO glass in this measure before rupturing. This intensity is not fully concentrated on the first order due to a loss of the blazed profile of the grating towards a more sinusoidal profile. Also, from this point, going back to 0 Vpp, the order shows a progressive increasing of the intensity until reach almost all the starting intensity.

The figures 5. (b) and (c) show the intensity of the first order as a function of the applied voltage for a 160 μm and 80 μm period blazed gratings. This order shows an increase of the intensity with the Vpp applied, slightly higher for the 80 μm blazed grating and higher than 10% in both cases.



a)

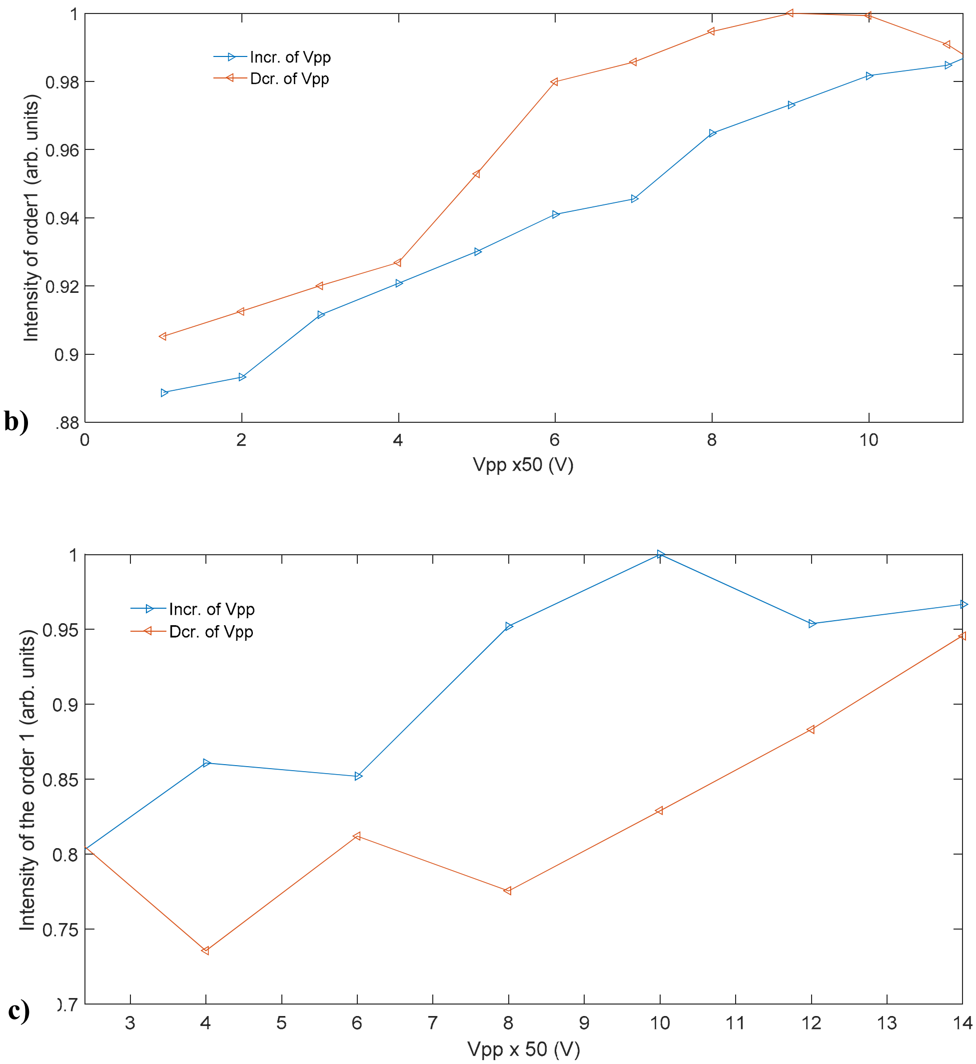


Figure 5. (a) Intensity of the main order as a function of the applied voltage for a 1448 μm blazed grating, (b) Intensity of the main order as a function of the applied voltage for a 160 μm blazed grating, (c) Intensity of the main order as a function of the applied voltage for an 80 μm blazed grating.

4. CONCLUSIONS

Along the paper we have studied the behavior of a PDLC material to record blazed gratings of different periods using a LCoS display. Using this device, we have been able to store blazed gratings with periods from 1448 μm to 40 μm with an accurate control of the phase and amplitude. The high potential of the LCoS combined with other devices has permitted us to record and analyze on real time the formation of the gratings onto the PDLC photopolymer and measure the DE of different grating periods, reaching more than the 20% of DE in all the cases.

After the recording of the DOE, the grating has been placed into an electrical field to evaluate the electro optical response of the gratings, measuring the changes of the main and first orders for grating of different periods. In this case we have observed a decreasing of the main order with the increasing of the Vpp and an increasing of the first orders with the Vpp. For the zero order, the diminution of the 80% of intensity have been shown as well as an increment of more than the 10% for the gratings with periods of 160 μm and 80 μm.

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